On-orbit Calibration of a Multi-Spectral Satellite Sensor Using a High Altitude Airborne Imaging Spectrometer

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ABSTRACT

Earth-looking satellite sensors must be calibrated in order to quantitatively measure and monitor components of land, water and atmosphere of the Earth System. The inevitable change in performance due to the stress of satellite launch requires that the calibration of a satellite sensor be established and validated on-orbit.

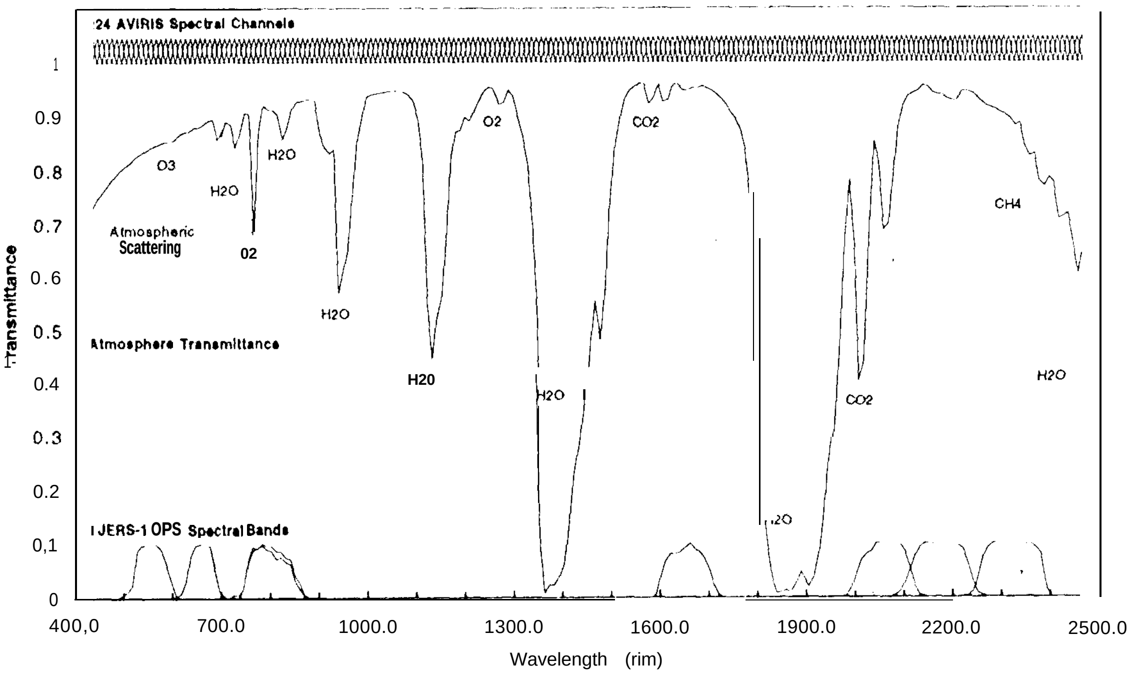
A new approach to on-orbit satellite sensor calibration has been developed using the flight of a high altitude calibrated airborne imaging spectrometer below a multi-spectral satellite sensor. This strategy was implemented on the 27th of August 1992 for the Optical Sensor (OPS) on board the Japanese Earth Resources Satellite-1 (JERS- 1) using NASA's Airborne Visible-Infrared Imaging Spectrometer (AVIRIS). Calibrated AVIRIS spectral radiance data were acquired beneath OPS. OPS has eight spectral filters and eight detector arrays with 4096 elements to measure each of eight spectral bands in the solar reflected spectrum across a 75 km ground swath. AVIRIS calibrated data were spectrally convolved and spatially registered to the OPS data in the overlapping image area measured by the two sensors. The convolved and registered AVIRIS radiance data were used to determine the 32,768 on-orbit radiometric calibration coefficients required for calibration of the full 75 km swath and eight spectral bands of OPS.

1.0 INTRODUCTION

Earth-looking satellite sensors must be calibrated in order to: (1) derive physical parameters from the radiance measured at the top of the atmosphere; (2) compare data acquired from different regions and from different times; (3) analyze and compare data with data acquired by other instruments; and (4) compare and analyze data with results from computational models.

Calibration of satellite sensors must be established and validated post-launch for the on-orbit environment under which operational data arc measured. This requirement results from the difficulty 01 accurately calibrating a satellite sensor in the laboratory environment and the likely change in calibration duc to the "trauma" of launch and effects of satellite out-gassing as well as the change in gravitational, temperature and radiation environment of Earth orbit.

The objective of this research was to develop a new approach to on-orbit calibration of a multi-spectral satellite sensor by using simultaneous under-flight of a calibrated high altitude airborne imaging spectrometer (Green et al., 1993). This strategy was implemented for the Optical Sensor (OPS) on board the Japanese Earth Resources Satellite- 1 (JERS - 1) using NASA's Airborne Visible-lnirared Imaging Spectrometer (AVIRIS). On-orbit calibration of OF'S using AVIRIS was enabled by the overlapping spectral coverage of OPS and AVIRIS (Figure 1).



Figure]. This plot shows the eight spectral bands of OPS and the 224 narrow spectral channels of AVIRIS in the solar reflected spectrum. A transmittance spectrum of the Earth's atmosphere is also shown. OPS band 3 and 4 overlap in the spectrum.

2.(I OPS AND AVIRIS SENSORS

JERS-1 was launched February 11, 1992 with OPS. OPS measure the Earth with eight spectral bands in the solar reflected spectrum from 400 nm to 2500 nm. Band's onc through four measure the visible and near-infrared (VNIR) portion of the spectrum. Band's five through eight measure the short wavelength infrared portion of the spectrum (SWIR). The full width at half maximum throughput of these bands ranges from 60 nm to 130 nm. These eight bands measure the upwelling radiance at the top of the atmosphere. The digitization of OPS is 6 bits. OPS measures images with a satellite cross-track swath width of 75 km and a cross-track spatial sampling of approximately 18 m. Each spatial cross-track element for each spectral band of OPS is measured by a different detector and different path through the optics and filters of the sensor. There are 32,678 unique detector-filter combinations that must be calibrated in OPS.

NASA's Airborne Visible/Infrared imaging Spectrometer (AVIRIS) is an Earth-looking imaging spectrometer that operates from a high altitude aircraft at 20,000 m. AVIRIS measures spectra of the total upwelling radiance from 400 nm to 2500 nm at 10 nm intervals. These spectra arc measured by 224 detector elements receiving light from a fore optics through four spectrometers. AVIRIS images arc acquired with a scan mirror such that each spatial resolution element in the image is measure. d by the same optical, spectrometer and detector system. Images arc 11 km wide by up to 1()() km long with spatial sampling of 17 m by 17 m and 20 m by 20 m spatial resolution. AVIRIS data were digitized at 10 bits through 1994 and then improved to 12 bits for later years. Radiometric, spectral and spatial characteristics of AVIRIS are calibrated in the laboratory twice pcr year (Chrien et al., 1990). The standards for the laboratory calibration are, respectively, a National Institute of Standards and Technology irradiance source, a mercury low pressure emission line source, and a narrow precision slit light source. Calibration of AVIRIS has been incrementally improved each year (Sarture et al. 1995). The laboratory calibration is validated multiple times during the night season through in-flight calibration experiments (Conel et al., 1988, Green et al., 1990). These experiments compare the constrained radiative transfer code predicted spectral radiance for a fully characterized ground calibration target with the laboratory calibration trace spectral radiance measured in-flight for the target. In 1992 and later, these validation experiments showed AVIRIS to be calibrated at 95 percent accuracy or better (Green et al. 1993, Green et al. 1996).

3.0 OPS AND AVIRIS DATA SET

On August 27, 1992, JERS-1 OPS measured a portion of the Mojave Desert, California centered at latitude 34.92 degrees and longitude -117.71 degrees at 18:48:08 UTC. This region is located approximately 100 km north of the city of Los Angeles, on the southwest coast of the United States. The OPS data set included the eight spectral bands and were received as the 6 bit digitized numbers (DN) recorded at the satellite sensor. Simultaneous with the OPS data acquisition, AVIRIS acquired a spectral image flight-line across the complete 75 km swath of the OPS image (Figure ?). The. AVIRIS data set included the full spectrum from 400 nm to 2500 nm at 10 nm intervals calibrated to total upwelling spectral radiance (Green et al., 1992)

Figure 2. OPS Image Of The Mojave Deserts, California Acquired On August 27, 1992. The Simultaneous AVIRIS Under-Flight Image Is Superimposed.

'J'o assess the JERS-1 OPS output for zero input signal an additional OPS data set was acquired when JERS-1 was in the Earth shadow over open ocean on March 11, 1992.

4.0 VALIDATION OF AVIRIS CAI.1BRATION

To further validate this on-orbit calibration approach for JERS- 1 OPS, an AVIRIS in-flight calibration experiment was carried out on Rogers Dry Lake, a homogeneous playa contained in the image. At a ground calibration target on Rogers Dry Lake, the surface spectral reflectance was measured with a field spectrometer and the aerosol and water vapor properties of the atmosphere were measured with a sun photometer. These measurements were used to constrain the MODTRAN3 radiative transfer code (Berk et al., 1989) and predict the total upwelling spectral radiance arriving at AVIRIS. This predicted radiance was compared with the AVIRIS measured radiance for the calibration target (Figure 3). The comparison showed that AVIRIS was calibrated at the 95 percent accuracy across the spectrum excluding strong water vapor absorption at 1400 nm and 1900 nm.

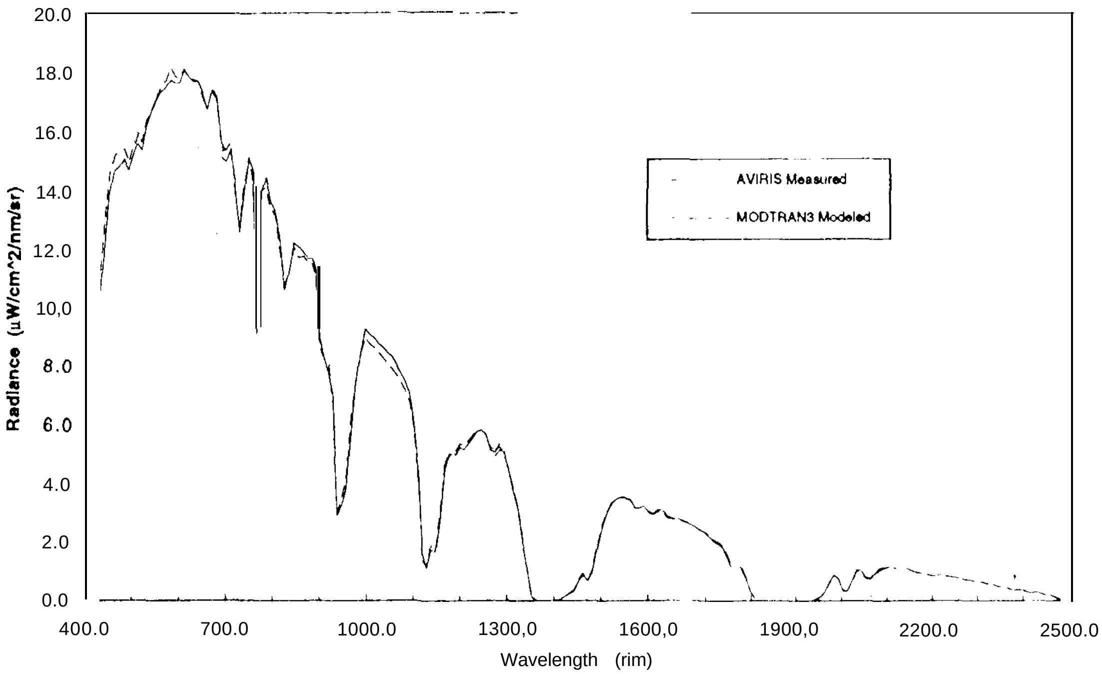


Figure 3. In-flight calibration experiment results that validate the calibration of AVIRIS at the 95 percent accuracy on August 27, 1992.

5.0 ANALYSIS AND RESULTS

For this approach, the AVIRIS measured spectral radiance must be extrapolated to the top of the atmosphere for use in the on-orbit calibration of OPS. The transmittance of the atmosphere from the 20 km AVIRIS altitude to the top of the atmosphere was calculated with MODTRAN3 and constrained by the sun photometer ozone determinations (Figure 4). The transmittance approaches unity with the exception of weak absorption due to ozone, oxygen and carbon dioxide in restricted portions of the spectrum. The AVIRIS spectral images were multiplied by this transmittance to extrapolate the AVIRIS measured radiance to the on-orbit OPS measurement environment. The magnitude of this extrapolation is less than 0.5 percent except for OPS band one where the magnitude is 2.5 percent due to stratospheric ozone.

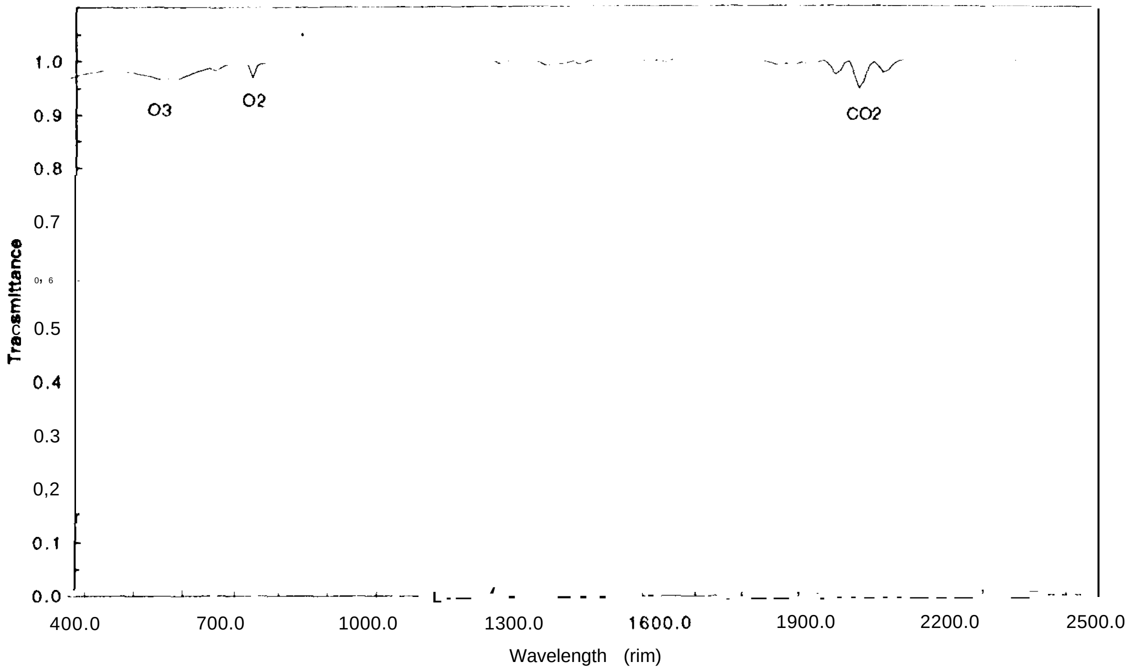


Figure 4. Transmittance from 20 km altitude of AVIRIS measurement on a NASA ER-2 flying at 20,000 m altitude to the top of the atmosphere.

At the time of the OPS acquisition, the solar zenith angle was 29.374 degrees. During the time AVIRIS flew across the OPS swath, the solar zenith angle changed from 29.784 to 29.294 degrees. A calculation of the solar zenith angle along the AVIRIS flight-line was used to correct the AVIRIS spectra to the solar illumination for the OPS acquisition. The maximum correction was 0.4 percent.

AVIRIS measures the total upwelling radiance as spectra from 400 nm to 2500 nm at 10 nm intervals. To calibrate OPS with AVIRIS the spectra must be convolved to the eight OPS spectral bands. A splint interpolation algorithm was developed and used to interpolate the measured spectral response functions for the eight OPS spectral bands (Figure 5) to a set of spectral response functions that correspond to the AVIRIS spectral channel positions (Figure 6).

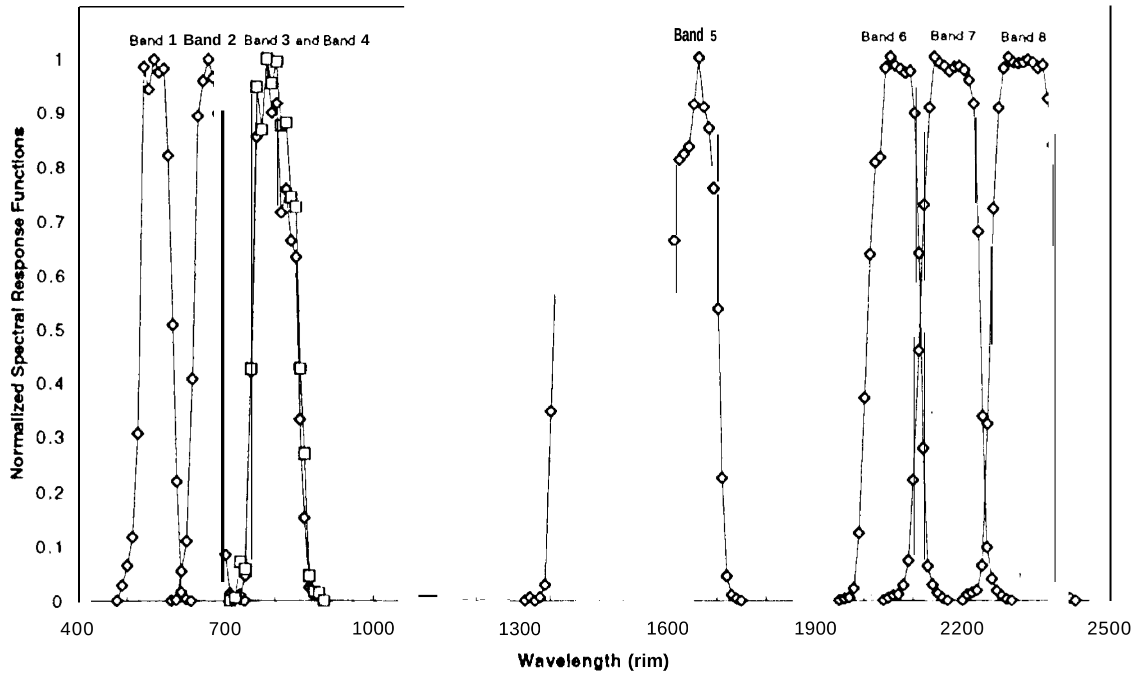


Figure 5. Measured spectral response functions for the eight OPS spectral bands. Bands' three and band four have overlapping spectral response functions. The diamond and square symbols show the measurement positions.

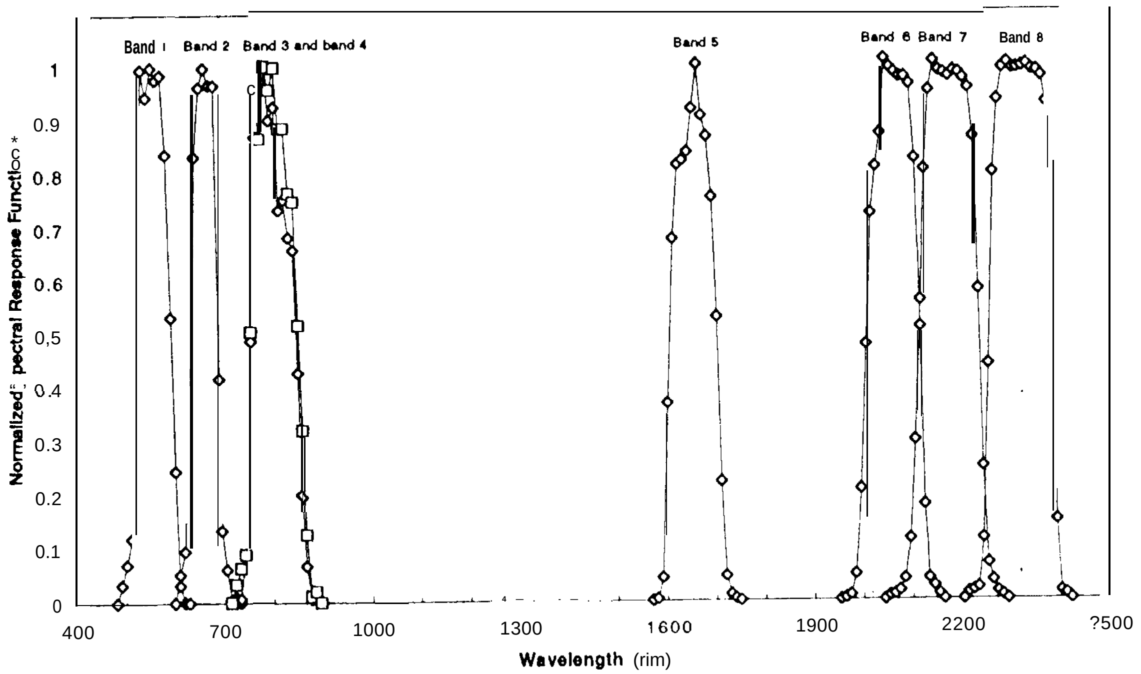


Figure 6. Eight spline interpolated OPS spectral response functions that correspond to the positions of the AVIRIS spectral channels in the region from 400 nm to 2500 nrn. The symbols show the AVIRIS channel positions.

A spectral convolution algorithm was developed to generate the weighted spectral response functions (Figure 7) and apply them to the measured AVIRIS spectra to produce eight AVIRIS derived OPS' spectral bands. For each AVIRIS derived OPS' spectral band i, the radiance 1.(i) is the sum of the product of the weighted spectral response function wSRF(c) and the AVIRIS radiance 1.(c) for each AVIRIS channel c (Equation 1).

$$I.(i) = \Sigma \, wSRF(c) * I,(c) \qquad (1)$$

For example, this algorithm was applied to a calibrated AVIRIS spectrum from Rogers Dry Lake (Figure 8). Uncertainty in the AVIRIS derived OPS' bands was calculated from the uncertainty of the laboratory calibration of AVIRIS. The weighted spectral convolution algorithm was applied to the entire AVIRIS flight-line generating images corresponding to the eight OPS spectral bands across the 75 km Mojave image swath (Figure 9).

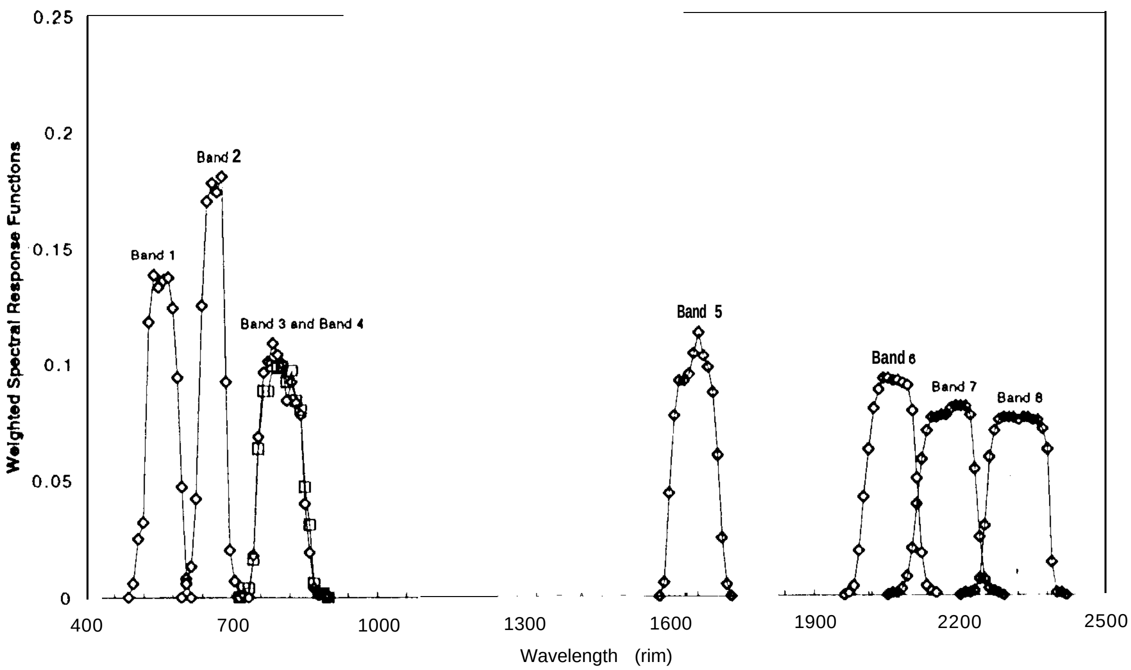


Figure 7. Eight weighted splint interpolated OPS spectral response functions that correspond to the positions of the AVIRIS spectral channels. The symbols show weighting values at the AVIRIS channel positions,

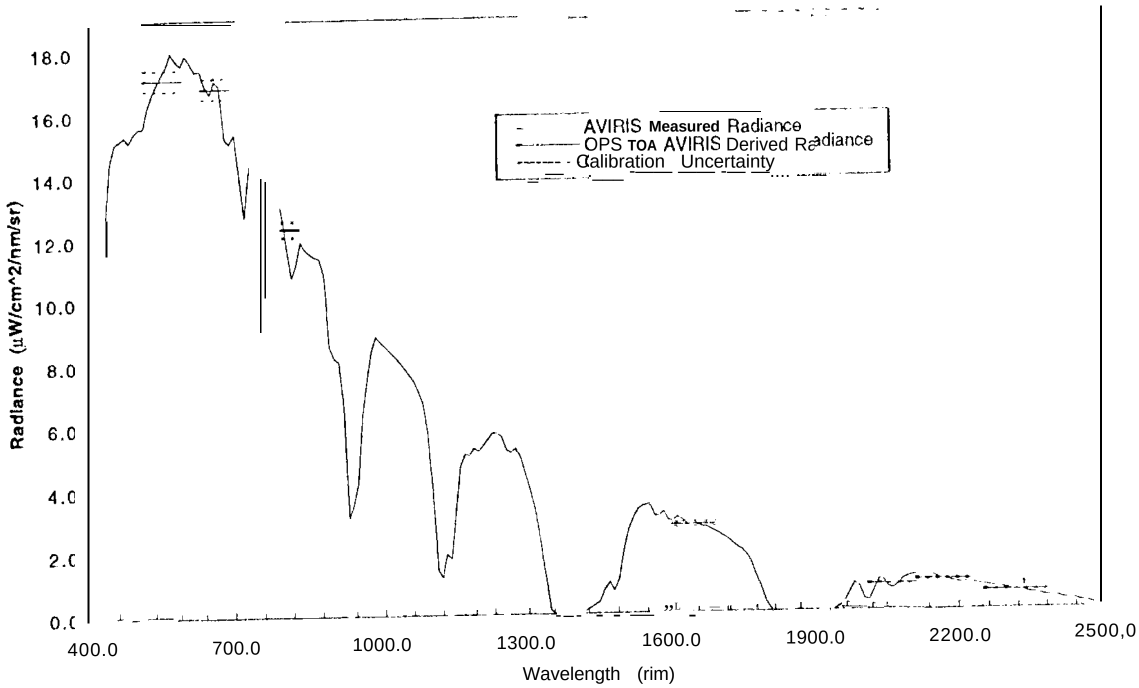


Figure 8. AVIRIS measured spectrum for the calibration target on Rogers Dry Lake and the corresponding eight OPS' spectral bands generated from the calibrated AVIRIS spectrum. Calibration uncertainty calculated from the AVIRIS laboratory calibration is shown.

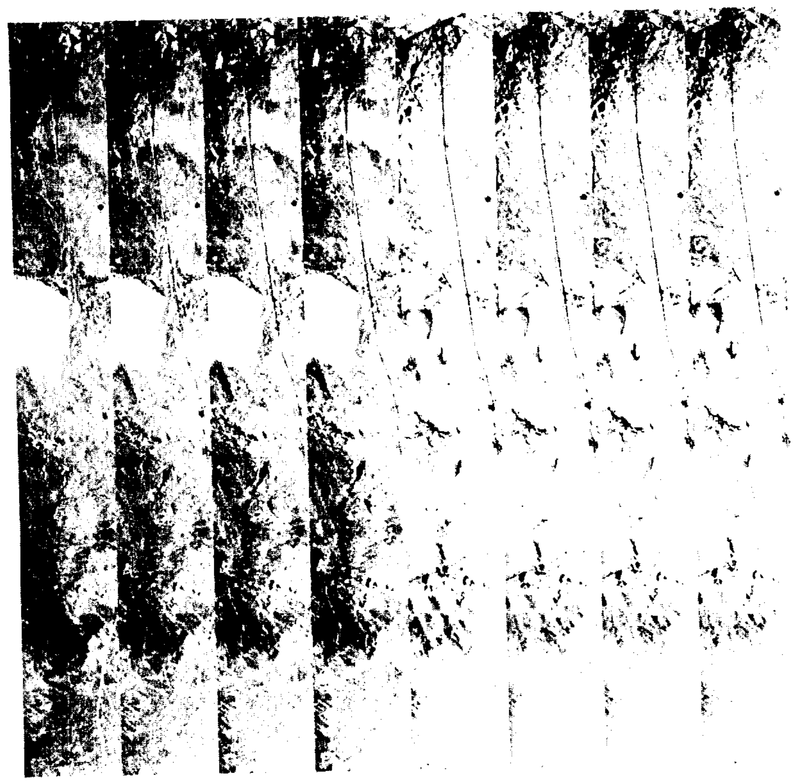


Figure 9. images of the eight AVIRIS derived OPS' spectral bands produced from a weighted spectral convolution of the interpolated OPS spectral response functions with the AV11<1 S spectra for the flight-line acquired beneath JERS- 1.

Each of the AVIRIS derived OPS' bands were registered to each of the corresponding JERS- 1 OPS measured images (Figure 2). The AVIRIS data set was sufficiently long to account for the differing starting alignments of the eight OPS bands. A third order polynomial registration algorithm was used based on 150 ground control points between the OPS and AVIRIS images. AVIRIS OPS data were spatially resampled to overlay each of the eight OPS band images with nearest neighbor algorithm.

For the region of overlap, the JERS- 1 OPS digitized numbers (DN) were averaged for the satellite down-track spatial elements. This was done for each of the eight spectral bands (Figure 10). An odd-even difference in the DN of adjacent spatial elements is apparent at varying levels in the OPS bands. A decrease in DN response at the edges of the OPS cross-track swath versus the center is evident in the SWIR bands with respect to the VNIR bands. In the image data, the OPS SWIR bands also exhibit apparent down-track smearing. In this calibration analysis, the effect of the smearing was mitigated through the down-track averaging, The registered AVIRIS derived OPS' bands, in units of top of the atmosphere radiance, were identically averaged for satellite down-track spatial elements in the region of overlap (Figure 11).

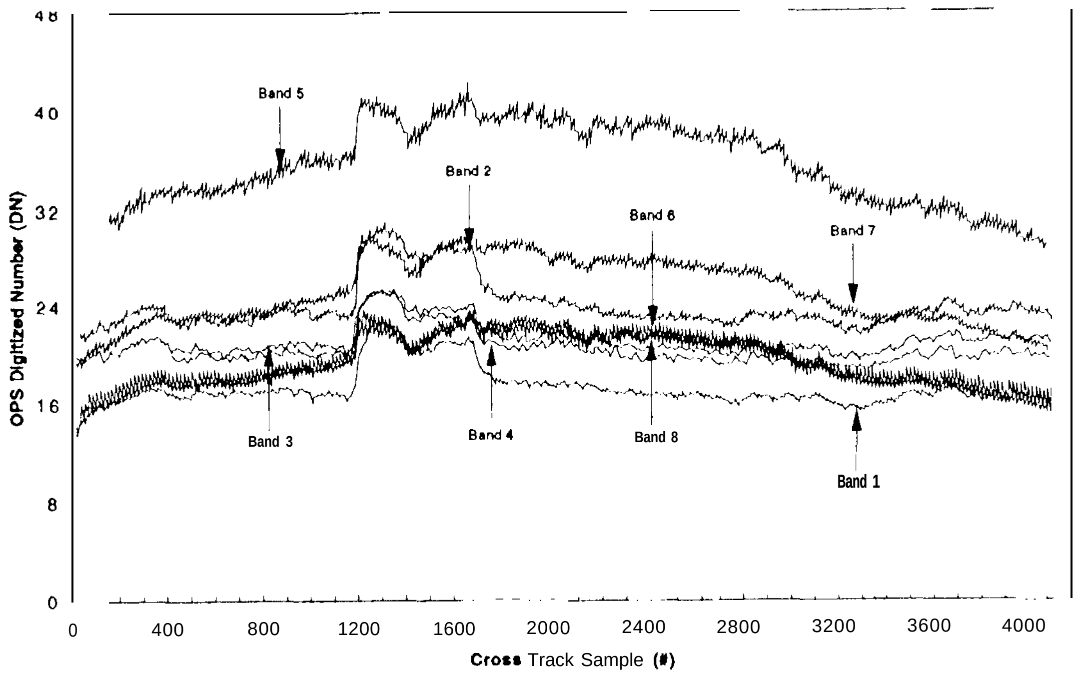


Figure 10. Down-track averaged JERS- 1 OPS DN across the 75 km OPS swath for the region of OPS and AVIRIS image overlap. A plot of all 4096 cross-track values overly compresses the expression of cross-track odd-even response differences in OPS, therefore only every sixteenth and seventeenth value are shown in (he plot.

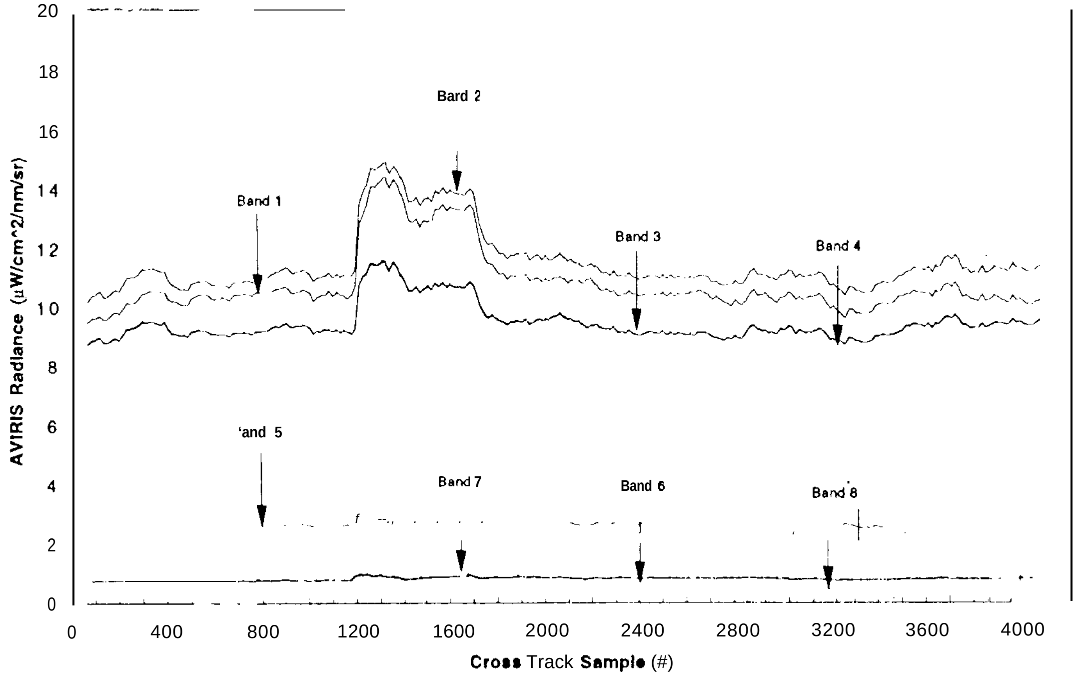


Figure 11. Calibrated AVIRIS derived OPS' for the eight spectral bands across the JERS- 1 OPS swath in the region of image overlap. Every sixteenth and seventeenth value is shown.

The JERS- 1 OPS data set acquired in the Earth shadow was analyzed to determine the DN recorded with a zero signal level input (DN0). These DN0 values were calculated as the down-track average for each cross-track sample and each OPS. Rand six and seven exhibited significant DNO values that were a function of odd-even cross-track element (Table 1).

'l'able 1. JERS- 1 OPS Zero Signal Levels

Band	Odd	Even
1	0.00	0.00
2	0.00	0,00
3	0.00	0.00
4	0,00	0,00
5	0.00	0.00
6	0.96	0,00
7	0.00	0.84
8	0.00	0,00

The on-orbit radiometric calibration coefficients were calculated for each OPS spectral band as the AVIRIS derived OPS' radiance divided by the JERS-1OPS measured DN with DN0 subtracted for each cross-track clement in the OPS swath. The eight OPS bands and 4096 cross-track elements result in the calculation of 32,768 radiometric calibration coefficients (Fig ure 12). To simplify the reporting of these results, an equation has been developed to express the radiometric calibration of JERS-1OPS derived from the AVIRIS under-flight (Equation 2). On-orbit radiance 1. for OPS in units of ($\mu W/cm^2/nm/sr$) is calculated as a function of band i, digitized number DN, zero signal level DNO, radiometric calibration coefficient RCC, cross-track sample s and odd-even sample position oe. Analysis of the odd-even cross-track response difference over a range of bright and dark targets in the set of AVIRIS derived radiometric calibration coefficients lead to the inclusion of an additional odd-even multiplicative correction factor OE (Table 2) as part of the OPS calibration equation.

$$L(i) = [(DN(i,s) - DN0(i,oe)) * RCC(i,s)] * OE(i,oe) \tag{2}$$

A second order polynomial equation has been developed to model the radiometric calibration coefficients for each OPS band as a function of cross-track sample (Equation 3). This polynomial has coefficients that arc a function of OPS band (Table 3).

$$RCC(i,s) = a(i) + b(i) * s + c(i) * S^2 \tag{3}$$

'l'he calculated radiometric calibration coefficients compensate for up to a 25 percent change in cross-track response in the SWIR OPS bands. The odd-even correction factor compensates for an odd-even difference in response of up to 6.8 percent in OPS bands.

Table 2. JERS- 1 OPS Odd-Even Cross-Track Sample Correction Factor

Band	Odd	Even
1	0.995	1.005
2	1.009	0.991
3	0.999	1,001
4	1.000	1.000
5	0.987	1.013
6	0.966	1.034
7	1.012	0.988
8	1.019	0.981

Table 3. Parameters for Calculation of Cross-Track Radiometric Calibration Coefficients for JERS- 1 OPs

Band	a	b	c
1	6.07E-01	1.90E-05	-3.58E-09
2	4.69E-01	8.08E-06	1 .34E-09
3	4.58E-01	1.92E-06	1.3513-09
4	4.46E-01	3.09E-06	-6.21E-10
5	8.71E-02	-1.89E-05	4.92E-09
6	4.70E-02	-9.46E-06	2.43E-09
7	3.86E-02	-8.08E-06	2.12E-09
8	2.99E-02	-6.61E-06	1.69 E-09

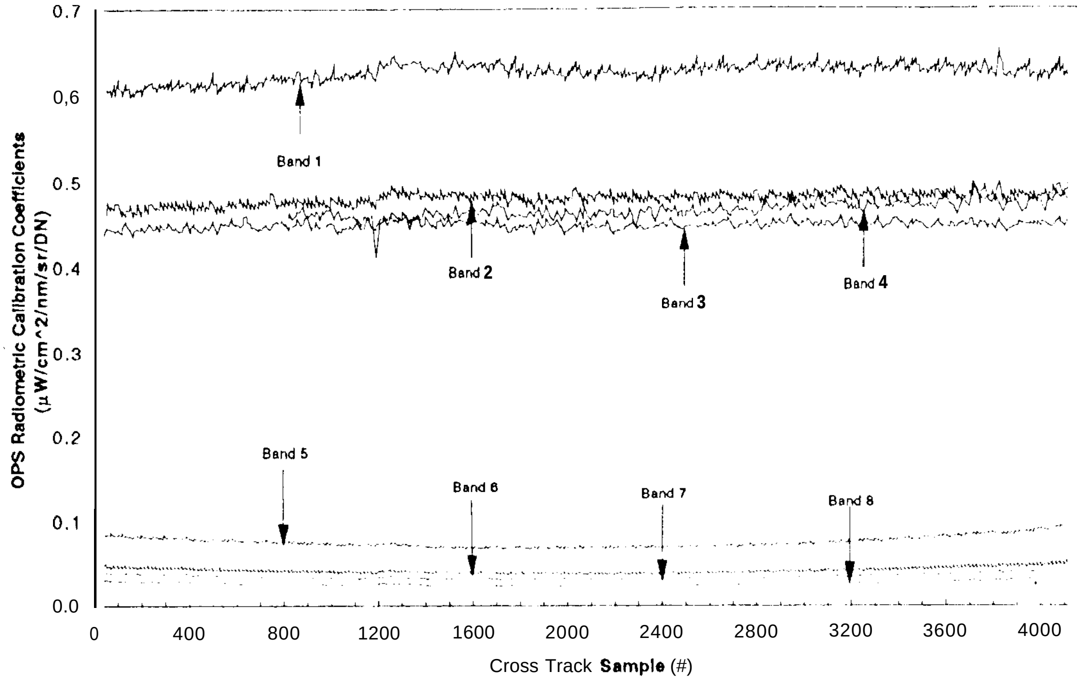


Figure 12. On-orbit radiometric calibration coefficients for the full swath and eight spectral bands of JERS- 1 OPS derived from the under-flight of AVIRIS. For clarity, only every sixteenth and seventeenth value arc shown.

Uncertainty in the AVIRIS derived radiometric calibration coefficients for OPS was calculated based on the AVIRIS laboratory calibration uncertainty and was validated in-flight. This uncertainty in the AVIRIS derived on-orbit calibration is given in terms of the polynomial coefficients for the uncertainty in radiometric calibration coefficients (Table 4). These coefficients allow calculation of the uncertainty in radiance units across the OPS swath (Equation 2 and Equation 3).

Table 4. Parameters For Calculation Of The Uncertainty In The Cross-Track Radiometric Calibration Coefficients For JERS- 1 OPS

Band	a	b	c
1	1.15E-02	3.60E-07	-6.79 E-11
2	9.39E-03	1.76E-07	-2.68 E- 11
3	9.62E-03	4.04 4E-08	2.83E-011
4	9.37E-03	6.49E-08	- 1.30E:-11
5	2.35E-03	-5.11E-07	1.33E-11
6	1.87E-03	-3.65E-07	9.39E-11
7	1.63E-03	-3.33E-07	8.74E-11
8	1.64E-03	-3.64E-06	9.31E-11

This research and analysis has generated the full set of radiometric calibration coefficient for JERS- 1 OPS. When applied to the measured OPS DN, these equations and calibration parameters compensate for difference in cross-track and odd-even response and generate calibrated OPS radiance ($\mu W/cm^2/nm/sr$) at the satellite. These calibration parameters are valid through time as a function of the stability of the OPS sensor on-board the JERS- 1 satellite.

6.0 DISCUSSION

Earth-looking satellite sensors arc being developed with detector arrays ranging from hundreds to thousands of cross-track elements. Each detector receives energy through a distinct path through the sensor optics and filters. There arc differences in uniformity and stability in these detector, filter, optical components and therefore, each cross-track element must be calibrated. The surface of the Earth lacks the enormous homogeneous, stable ground calibration targets where the surface and atmosphere may be independently characterized and used to calibrate the full cross-track swath of these satellite sensors. Underflight of a calibrated high altitude airborne imaging spectrometer, such as AVIRIS with only 224 detectors to calibrate, enables this new strategy for establishment and validation of the on-orbit calibration of these satellite sensors.

This approach may be used to pursue satellite sensor calibration objectives beyond those presented. For example, periodic under-flight calibrations may be used directly to monitor on-orbit calibration. Additional AVIRIS data sets have been acquired beneath JERS- 1 OPS for this objective. Alternatively, the airborne imaging spectrometer based calibration may be used to establish and validate the calibration of an cm-board calibrator on a satellite sensor. The on-board calibrator may then be used for high frequency monitoring of the calibration. Under-ili~hts of different satellites may be used for sensor cross-comparison and inter-calibration. Furthermore, the high spectral, high spatial and high radiometric resolution of an airborne imaging spectrometer, in conjunction with stability and uniformity, support investigation of spectral and spatial scattered light in satellite sensors in Earth orbit, This approach is important for current and future large spatial resolution sensors where the calibration of many 1 km by 1 km resolution elements is easily achievable with an airborne imaging spectrometer and exceedingly difficult by any other means. investigation of linearity as well as spatial and spectral calibration of on-orbit satellite sensors is also feasible.

7.0 CONCLUSION

A new approach to on-orbit calibration of Earth-looking satellite sensors measuring radiance in the solar reflected spectrum has been developed and demonstrated, This method calibrates the satellite sensor using the Earth's radiance in a fully operational environment.. The multi-spectral OPS on-board the JERS- 1 Satellite has been calibrated on-orbit using this method with an under-flight of NASA's AVIRIS imaging spectrometer, The calibration of AVIRIS was simultaneously validated with an in-night calibration experiment. For OPS the full set of 32,768 on-orbit radiometric calibration coefficient were derived to calibration the eight spectral bands across the 4096 cross-track samples of the 75 km OPS swath,

In addition to establishing the calibration of OPS on-orbit, this approach provides an independent pathway that is distinct from laboratory calibration or on-board calibration methods. Independent calibration pathways arc required to validate the calibration of sensors on-orbit initially and through time.

Increasingly rigorous calibration requirements are being established for Earth-looking satellite sensors to support physically based data analysis and measurement and monitoring of the Earth system through time. Calibration of satellite sensors must be established and validated on-orbit where the operational objectives of the sensor arc accomplished. A calibrated high altitude airborne imaging spectrometer enables a new strategy for the on-orbit calibration and validation of satellite imaging sensors with a range of spatial, spectral and radiometric resolutions in the solar reflected spectrum.

8.0 ACKNOWLEDGMENTS

This research was primarily carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. A portion of these analyses were carried out at the Institute for Computational Earth System Science at the University of

California, Santa Barbara, California. This re.search was jointly sponsored by the National Space Development Agency of Japan and NASA.

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